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3D APPLICATION STUDY

IIT Research Institute

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This effort considered ways in which the application of three dimensional display technology could improve task performance in the battle management arena. A subset of a typical Air Force C^3I battle management application was analyzed to evaluate how 3D display technology could aid in task performance. Appropriate C^3I applications were studied to determine the categories of problems that might benefit most from anticipated 3D capabilities. Various approaches for the generation of three dimensional images were investigated in order to determine their potential applicability to the identified problem areas. Different technologies and techniques for 3D image generation were examined, and the feasibility of their application was assessed. Finally, a demonstration of the use of 3D in support of an approved application was developed. In specific, 3D benefits were identified, commercially available equipment was evaluated and acquired, and a demonstration system was developed to illustrate the use of 3D in a C^3I application. This report presents the results of this study effort.

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FOREWORD

This is the Final Technical Report, CDRL No. C003, for Task 3 under contract F30602-87-D- 0094. This contract is with IIT Research Institute (IITRI) and sponsored by Rome Air Development Center. The work was performed by IITRI, Rome, NY; Honeywell SRC, Minneapolis, MN; Merit Technology, Plano, TX; and SRI International, Menlo Park, CA.

3D APPLICATION STUDY

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Introduction

The purpose of this effort was to consider ways in which the application of three dimensional display technology could improve task performance in the battle management arena. Three tasks comprised this effort. The first was the analysis of a subset of typical Air Force C3I battle management applications to evaluate how 3D display technology could aid in task performance. Toward this end, appropriate C3I applications were studied to determine the categories of problems that might benefit most from anticipated 3D capabilities. The second task was the investigation of various approaches to the generation of three dimensional images in order to determine their potential applicability to the problem areas identified in Task 1. Different technologies and techniques for 3D image generation were examined, and the feasibility of their application to the problem areas of interest was assessed. The third task called for the demonstration of the use of 3D in support of an approved application. In support of this task, specific 3D benefits were identified as providing improved capabilities, commercially available equipment was evaluated and acquired, and a demonstration system was developed that would illustrate the use of 3D in a C3I application. This report presents the results of the study phase of the effort. Delivered as a separate document with the Final Report is the User's/Operator's Manual for the demonstration software.

Depth Perception

Most people are familiar with monocular depth cues, such as nearer objects occluding more distant ones, linear perspective and shadows cast by lighting. The 3D display of images requires a binocular perception of the image and allows the viewer to synthesize a three dimensional image of the scene that more accurately represents the relative position and size of objects in the scene. The primary benefit to be gained from the display of information in three dimensions is that it allows the user to perceive these relationships rather than require him to cognitively translate tabular or two dimensional data into an internal representation with 3D characteristics. These perceptual benefits are of four major types: a more rapid and accurate grasp of spatial features, improved scaling of physical attributes such as distance and velocity, disambiguation/decluttering of graphic and textual information on a display, and the ability to interactively simulate abnormal sensorimotor relationships such as those found in microgravity.

There is also evidence for potential cognitive benefits of 3D displays. The ease and effectiveness with which the mind processes information relates directly to the form in which the information was presented. The additional dimension provided by 3D displays allows trainers at the Interceptor Weapons School, for example, to clearly demonstrate the effects of the timing of a turn on the geometry of the intercept. 3D displays can also facilitate information retention and retrieval. Another promising area in terms of cognitive benefits is that of anticipation/expectation. By providing displays of synthesized data that relate directly to the pilot's immediate

decision making process; it is possible to reduce the information load on the pilot.

3D in C3I Applications

In light of the possible benefits that 3D displays could provide, an analysis was conducted to determine which C3I applications might expect to see the greatest improvement in task performance as a result of applying 3D display technology. This analysis considered the types of data appropriate for 3D displays and specific unique benefits that 3D might provide, then mapped them to specific battle management applications.

Data suitable for representation in three dimensions falls into either of two categories. The first and the most obvious is that of data with inherently spatial characteristics. This includes both objects that may exist in space, such as aircraft and terrain, as well as more abstract data, like a volume representing radar coverage at a particular sensitivity. The other type of data appropriate for display in three dimensions lacks spatial features, but uses the third dimension for other values. Various forms cf networks showing relationships between complex sets of variables are an example of the growing field of data visualization.

Three tentative benefits resulting from the use of 3D displays for C3I applications were identified during the course of this study. Decluttering an image allows a user to view a large amount of information on a screen more easily without reducing the amount of data displayed. Information presented at different depth planes enables the viewer to selectively focus on data with less distraction. The second benefit was the ability to perceive irregularly shaped volumes. The form of regular geometric shapes can be inferred from 2D perspective representations, but irregularly shaped volumes, such as those depicting realistic electronic envelopes, cannot be adequately perceived by viewing the image imposed on a two dimensional surface. Finally, the perception of 3D images over time, as in a battlefield simulation, essentially allows the user to perceive a fourth dimension, that of time. This capability results in a more rapid and accurate estimation of speed, velocity and the time at which an object will reach a particular point in space or intercept another object.

Considering the types of data that lend themselves to 3D and the benefits that 3D can provide, two primary C3I functions were identified as the most promising for the application of 3D display technology. Situation assessment, though characteristically reliant on static displays of information, provides several opportunities to make effective use of two 3D features: movement over time and the representation of data by volumes. The historical movement of military and natural forces within the geographic area of interest could provide insights into the effects of terrain on movement and imparting a sense of distance between forces moving in three dimensional space. Similarly, force movement could be projected into the relatively near future to determine the possible consequences of current activity. More appropriate to situation assessment activities would be the use of 3D to provide a spatial view of electronic warfare equipment characteristics such as coverage, effective radiated power, and vulnerability to specific countermeasures. In the area of operational mission planning, 3D provides particularly appropriate capabilities. The visual modeling of mission execution from the viewpoint of the mission planner is perhaps the most obvious application. Another possibility, and a potentially more valuable one, is the simulation of a mission from the perspective of the mission pilot. Because of the scale and the real-time nature of the pilot's interaction with his environment, this is one of the most compelling candidate applications for enhancement by 3D display technology.

3D Display Techniques

Three dimensional display techniques can be grouped into two primary categories: stereoscopic and volumetric. Stereoscopic approaches involve the presentation of two slightly offset images of a view to each of the viewer's eyes. This offset duplicates the different perspective views of the two eyes, providing a perception of binocular depth. The problem associated with providing stereoscopic views is the manner in which the visual access to each eye is restricted to the appropriate image. Most systems require the user to wear some form of spectacles (colored or polarized) which separate the two images. Some, like the parallax panoramagram, are autostereoscopic and require no user-worn aids to separate the views to each eye. Of the stereo systems examined, the field sequential display with image separation at the source (requiring the viewer to wear passive polarized spectacles) represents the most mature technology and is commercially available for use with computer displays. Given an appropriately powerful graphics computer system, the addition of stereo capability can provide sufficient processing speed, display resolution and color for many battle management applications, particularly in the area of mission planning. The need to wear passive glasses is a minor inconvenience, and the use of polarized filters reduces available brightness significantly. Like all stereoscopic systems, the technique fails to preserve full motion parallax. When the viewer moves his head to the right, for example, the images do not reveal previously hidden surfaces as occurs in true three-space. Rather, they appear to move to the right as well. This effect can be a source of annoyance or confusion to the viewer.

Volumetric techniques attempt to create a three dimensional image as opposed to presenting two perspective views of a particular scene. Because of the spatial nature of their images, most volumetric systems have the advantage of being viewable by multiple observers without the need for user-worn aids. Holography is one technology that has generated a great deal of interest. Unfortunately, due to the processing time required for the production of solely static images, real-time applications are not expected to be available in the foreseeable future. A volumetric system that has been commercially marketed, however, is based on a varifocal mirror technique. The SpaceGraph system uses a vibrating mirror to reflect a two dimensional computer screen image. By synchronizing the display of points and lines with the oscillating silvered membrane, SpaceGraph essentially draws a three dimensional image in space. The result is a very compelling image. No aids are required to be worn by the viewer, and the number of viewers is limited primarily by the relatively small display space of the system. Unlike other available systems, this technique preserves full head-motion parallax. The most significant drawbacks of SpaceGraph are the lack of color capability due to current phosphor extinction rates and the limitations on the number of pixels that can be addressed when the mirror is in a particular position (in turn, limiting the complexity of displayed images). If some of these difficulties can be overcome, vibrating mirror technology offers a potential alternative to stereoscopic display systems.

SCENARIO 3D Demonstration System

In addition to the completion of this study, this effort required the development of a demonstration using a three dimensional presentation in support of a sample Air Force C3I battle management function. It was decided that the system should highlight the three situations in which 3D was felt to provide additional unique capabilities. The first of these is decluttering, in which elements of textual and graphical information displayed close together might be disambiguated by viewing them in their respective depth planes. An example of this would be in air space management, where information on multiple moving and overlapping objects must be discernable. The second was in the display of irregularly shaped objects and their intersection. While the viewer can imagine the shapes of regular geometric forms displayed on a 2D screen, the shapes of such forms as electronic threat envelopes can be very difficult to infer from a 2D representation. The third situation considered appropriate for a 3D display was the depiction of 3D data as it changes and moves over time, providing the viewer with the ability to project the time at which objects will reach a certain point or intersect with other objects. An outline was developed to exhibit 3D capabilities in a tactical air support situation in which the user is tasked to create a set of waypoints from a friendly airfield to an enemy target with a minimum exposure to threats, such as enemy radars and contaminated areas.

Hardware and software options for supporting the demonstration were considered. The eventual choice was the purchase of a Silicon Graphics graphics workstation with a StereoGraphics liquid crystal shuttering system. The decision was based largely on team familiarity with the system and the reasonable cost of systems used by Silicon Graphics for demonstration purposes. Given the limited time and budget for the development of the demonstration, these were both significant factors.

As implemented, the demonstration program, called SCENARIO, can use either of two terrain databases and provides the user with the ability to select between a 2D plan view of the scene, a 2-1/2D perspective view, and a 3D stereoscopic view. The user is able to display such features as electronic threat domes and dispersing contamination clouds while interactively defining the route of the aircraft and previewing the aircraft flying it in near real-time. The process of developing and reviewing the demonstration system provided insights into the use of 3D for operational tasks that had not been considered earlier. The stereo system is very sensitive to the parameters of the user's vision. The ease with which stereoscopic depth is perceived varies markedly for different people as well as for a single viewer during different sessions. By providing user control over the setting of the viewing parameters of the stereo system, the SCENARIO development team felt that the viewer could adjust them to maximum effect during the session and the software developer could experiment with the capabilities of the stereo technology.

The SCENARIO demonstration software provides the user with an example of 3D display technology applied to a battle management application. Project constraints in terms of team experience with 3D development, budget and time restrictions, and equipment performance capabilities necessarily limited aspects of the implementation. In most cases, these limitations can be overcome by further development of the system. In addition, the combined hardware and software provide a powerful and expandable stereo-equipped 3D graphics workstation for continued exploration and development. The SCENARIO source code contains examples of many aspects of stereo programming on the system, and its modular structure facilitates both enhancement of SCENARIO as well as the use of its modules in other programs.

Conclusions

The potential exists for achieving real and significant improvements in the performance of certain battle management activities as a direct result of the use of three dimensional displays. Primary anticipated benefits are a decluttered screen image providing greater accuracy and ease of use by the viewer; an improved accuracy in perceiving the mass, surface areas and intersections of volumetric forms; and an increased insight into the relationships of objects as they interact over time. C3I battle management functions within the scope of this study that can put these enhanced capabilities to the best use are in the areas of situation assessment and operational mission planning, particularly applications which involve the presentation of battlefield dynamics for purposes of evaluation. These situations make optimal use of the unique advantages of spatial and temporal modeling afforded by 3D displays.

The ability to realize the potential benefits of 3D displays is currently constrained by the state of the available technology. Several techniques provide compelling 3D images, but the problem of human vision variability and visual fatigue affects all 3D methods to some degree. In summary, three dimensional displays can provide the viewer with a perceptual reconstruction of three-space that is not achievable otherwise. The use of 3D may be particularly important when monocular depth cues alone provide ambiguous depth information. 3D can resolve those ambiguities, though depending upon the technology, it may be at the potential risk of some viewer discomfort.

1.0 INTRODUCTION

The purpose of this effort was to consider ways in which the application of three dimensional display technology could improve task performance in the battle management arena. Three tasks comprised this effort. The first was the analysis of a subset of typical Air Force C3I battle management applications to evaluate how 3D display technology could aid in task performance. Toward this end, appropriate C3I applications were studied to determine the categories of problems that might benefit most from anticipated 3D capabilities. The second task was the investigation of various approaches to the generation of three dimensional images in order to determine their potential applicability to the problem areas identified in Task 1. Different technologies and techniques for 3D image generation were examined, and the feasibility of their application to the problem areas of interest was assessed. The third task called for the demonstration of the use of 3D in support of an approved application. In support of this task, specific 3D benefits were identified as providing improved capabilities, commercially available equipment was evaluated and acquired, and a demonstration system was developed that would illustrate the use of 3D in a C3I application.

This report presents the results of the study phase of the effort. Section 2 provides a background discussion on the perception of depth in two and three dimensional images. Section 3 addresses candidate battle management applications from the perspective of unique 3D capabilities. Section 4 describes various techniques for the generation of three dimensional images. The discussion includes the advantages and disadvantages of the many approaches and is intended to acquaint the reader with the rich history and diversity of attempts to create synthetic three dimensional images. Section 5 documents the development and implementation of the demonstration system. The demonstration software User's/Operator's Manual is provided as a separate document. Section 6 summarizes the conclusions of the task, derived both from the study phase of the effort and the experience gained in developing the demonstration.

2.0 DEPTH PERCEPTION

2.1 Depth Perception in 2D vs. 3D

Almost everyone utilizes monocular depth cues; they are a fundamental visual function for most animals and are evident at very early stages of development. Monocular depth cues include:

- Linear Perspective: Euclid's law; i.e., the angular substance of an object of invariant linear size will be inversely proportional to the distance of the object from the eye.

- Detail Perspective: texture density also obeys Euclid's law.

- Aerial Perspective: Distant objects tend to have blurred contours and appear more bluish in appearance than closer objects.

- Interposition: Closer objects occlude farther objects along the same line of sight.

- Light and Shade: e.g., shadows cast by a directional light source.

- Motion Parallax: Transformations of the visual field resulting from movements of the head relative to a fixed environment.

- Relative Size of Familiar Objects: e.g., the approximate size of a car.

Algorithms for handling true perspective, edge blending, hidden line and surface removal, shading and light source location, contrast manipulation and animation in computer images exist to generate the monocular depth cues described above.

Both 3D and perspective 2D displays can present compelling depth cues that enable the viewer to localize displayed objects in three-space. 3D displays require binocular perception for full appreciation of depth, whereas 2D displays can be fully appreciated in monocular view. Because most depth cues are monocular (e.g., interposition, texture gradients, perspective), 2D displays can provide adequate depth rendition without the additional technical requirements imposed by 3D displays. The benefit derived from viewing 3D as opposed to perspective 2D displays is essentially the difference between perceptual and cognitive processing of visual information.

Because the two eyes view the world from different positions, the two retinal images are not identical; images of corresponding objects fall on different retinal locations in the two eyes. Within the fusional limits of the visual system, whenever disparate retinal images of the same object are presented to the two eyes, the visual system uses the disparity information to synthesize a three dimensional image of that object. When disparity information is absent, as when viewing a 2D display, depth is inferred solely from monocular depth cues. Frequently, and especially in synthetic images, monocular depth cues can be ambiguous; numerous visual illusions are based upon this ambiguity.

When information along a third dimension is imposed onto a two-dimensional image - even one containing monocular depth cues - an appreciation of that information may require cognitive processing. For example, when position along the Y-axis is used to encode some other dimension (e.g., probability of detection by radar), a comparison of Y-values at several X-Z locations requires examination of the relative distances of the Y-values from the X-Z plane. Because the X-Z plane must be shown in perspective view, estimation of the relative Y-values requires cognitive transformation of the X-Z plane, usually into plan view. The same information presented in a spatial form where depth is visually perceived will provide the viewer with immediate perceptual information about the relative locations of the two Y-values. The transformations are inherent in the pattern of retinal disparity that the visual system used to generate the depth percept.

One major advantage of 3D displays is their ability to disambiguate object locations, especially under relatively impoverished viewing conditions, as when image contrast is reduced or the images are blurred, e.g., by vibration. A situation in which depth ambiguity may occur is when objects are imbedded within a cluttered environment. Here the monocular depth cues may fail to provide sufficient depth information to define the locations of specific objects, but information added by the perceived position of objects in depth may be sufficient to permit discrimination of objects whose relative positions had previously been ambiguous. The potential benefits of 3D in this case would be an increase in accuracy in discrimination tasks, such as identifying a particular aircraft in a dense pattern, and a reduction in the error rate in detection tasks, such as when two aircraft are separated only on the Z-coordinate axis of an airspace.

Three dimensional displays that are applicable to C3 present synthetically generated representations of three-dimensional images. These representations do not mimic actual viewing conditions precisely, and this imprecision has important consequences. There are, for example, visual image requirements, peculiar to some types of stereoscopic displays (e.g., field-sequential, color-anaglyph, and polarization displays discussed in Section 4) that must be met before stereoscopic depth can be appreciated. If they are not met, the viewer may experience a delay in perceiving depth or may be unable to perceive stereoscopic depth at all. When such visual requirements are unmet, the usual result is diplopia, an undesirable condition in which the viewer perceives both monocular images, i.e., experiences double vision. Diplopia degrades visual performance significantly, and is to be avoided at all cost.

Volumetric displays, such as the varifocal-mirror types, do not use artificial means to separate the two images, so diplopia is not experienced when viewing displays of these types. However, these, as well as the field-sequential types, can produce flicker. Flicker can be more than an annoyance; it can contribute to another potential difficulty that viewers may experience with stereoscopic displays, that of "visual fatigue".

Visual fatigue is a poorly defined, but universally experienced phenomenon that has many causes. In the case of stereoscopic displays, some of the causes of visual fatigue are flicker, misalignment of the stereopair, and differences in the size, color, or brightness of corresponding objects in the stereopair. Visual fatigue can also be attributed to conflicting accommodation and convergence requirements. The accommodation/convergence conflict can create serious problems for the viewer of stereoscopic displays. When viewing a display screen, the eyes accommodate, i.e., focus on the display surface and the eyes converge so that they fixate the same point on that surface. However, the stereoscopic images presented on the display are not constrained to appear in that surface plane. They may appear to standout from the surface, in which case the eyes must accommodate and converge for a closer object, or they may appear to recede, which produces the opposite accommodative and convergence stimulus. Thus, the eyes are driven by conflicting accommodative/convergence stimuli between the screen surface distance and the object image distance.

2.2 The 3D Display of Information

The display of information in three dimensions, in contrast to conventional displays which are limited to two dimensions, provides a variety of benefits which can be divided into two categories: those which may be labeled 'perceptual', and those which fall into the 'cognitive' class.

2.2.1 Perceptual Benefits

The primary benefit to be gained from the ability to display information in three dimensions is the opportunity it affords to relieve the viewer of the need to cognitively translate tabular or two dimensional graphic data into an internal representation with 3D characteristics. Instead, the viewer can perceive more rapidly and clearly features such as depth and relative location. Perceptual benefits of 3D are of four general types: spatial features, scaling of physical attributes, disambiguation, and abnormal sensorimotor relationships. These are discussed in greater detail below.

The world in which we live is a three dimensional one, composed of objects that possess mass, occupy space and obey certain invariant rules of physics (e.g., more than one object cannot occupy the same space). A 3D display environment can provide a context within which objects and their relationships can be presented and interpreted in terms of familiar spatial and temporal features. For example, the flight profile of an aircraft or the navigation of a land vehicle might be easier to interpret when presented in the spatial context of terrain relief. Invisible but definable 3D areas, such as surface-to-air missile threat envelopes, can be displayed as volumes in space, providing a visualization capability not possible in the real world but obviously valuable when presented in a real world context. More creative uses of the technology are available to applications that are not bound by the constraints of real world references such as terrain. Molecular modeling, for example, is one field benefiting from the representation of spatial features using 3D displays.

The representation of objects in space can provide a scale by which estimates of physical attributes such as relative size, distance, altitude, velocity and acceleration can be derived. For example, the monocular depth cues available in the imagery from a navigation sensor can provide sufficient altitude information to support flight control under certain conditions. A real-time, interactive 3D display system can provide additional depth cues (primarily motion parallax cues) to generate a perception of speed and acceleration.

In the use of a two dimensional display system for graphics and time-sensitive applications, critical data and images can accumulate on the display to the point of distraction. Air traffic control is one example of an application where both graphic and textual information are necessary in a spatial context. The addition of another dimension (i.e., depth) affords a way of decluttering displayed information without necessarily reducing it. Perceiving graphic and textual data at different depths allows the user to focus on a particular depth plane and filter out competing visual stimuli. In interface design applications, the viewer is able to relate spatial position with a particular function such as the location of a pull down menu. Depth in this case need not be associated with physical distance, but can represent a conceptual attribute such as relative importance or response priority.

A fourth type of perceptual benefit of 3D displays is the unique opportunity they provide for simulating abnormal sensorimotor relationships such as those found in microgravity. This interactive simulation can play an important role in training. Evidence suggests that information about visual stimuli can be retained in Short Term Memory (STM) in a manner that conveys the physical properties of the elements composing the stimuli. In addition, studies of mental rotation and image scanning indicate that visual STM codes are processed much like actual physically present objects. STM or "working" memory is believed to be the site of ongoing, conscious activity. If STM visual codes strongly resemble the physical attributes of actual 3D structures, then performance and situation awareness might be enhanced if 3D visual stimuli are used in perceptual/motor tasks. When the normal relationship between proprioception (activation of sensory end organs in muscles, etc. that sense movement in the body) and vision is distorted, it has been found that adaptation to the new relationship is quicker when active (i.e., voluntary) movement is allowed than when the subject is only passively exposed to the change. In this vein, 3D displays would be beneficial for simulating the visual effects produced by "abnormal" sensorimotor relationships in pre-adaptation trainers.

2.2.2. Cognitive Benefits

Although the major advantage to the user of displaying information in 3D is the shifting of some tasks from cognitive to perceptual processes, there are potential cognitive benefits as well. Simply stated, cognitive processes are those functions performed by the brain to transform, manipulate, store, retrieve, analyze, evaluate and utilize information. For example, the increased perceptual correspondence that 3D provides of display imagery with our knowledge of the external environment can result in a reduction of mental workload and an enhanced situation awareness. The impact of 3D applications on the cognitive processes of information processing, data representation in memory, and anticipation/expectancy are discussed in the next three sections.

2.2.2.1 Information Processing

Although the term "information processing" is usually very broadly defined, for the purpose of this report it refers to those transformations of the visual signal that involve more "cognitive" concepts, such as memory.

The perception of a third dimension provides an additional dimension along which data can be displayed to represent how they are related to each other. A very natural application of 3D would be the display of terrain imagery where the relative distance and size of the terrain elements (e.g., trees, hills, structures) can be immediately and directly assessed. However, the concept of relating data using an "analog" representation (see Section 2.2.2.2 below) has also been adapted to develop a model by which declarative representations of situations, map data and events can be analyzed and described. This process, referred to as Topological Representation, is based on a formal logical theory of representation for situation assessment across two and three dimensional domains. These representations can form a knowledge base or be logically manipulated by symbolic inference algorithms. Topological Representation has been applied to route planning problems.

Dynamic networks also benefit from 3D representation. Dynamic networks can be pre-developed for an application (e.g., training, demonstration), or they can be interactive (e.g., man-in-the-loop simulation). Computer graphics simulation of dynamic three-dimensional airspace intercept tactics and geometry have been used as part of the Interceptor Weapons School (IWS) training program. According to Finegold, Asch, and Flaugher in their technical report, Simulated Three-dimensional Graphics Training Display for Air Weapons Controllers,

> "The primary training problem is the difficulty of effectively presenting the dynamic geometry involved in performing intercepts. For example, instructors cannot easily show students the effects of the timing of a turn on the geometry of the intercept, nor can they easily demonstrate how a heading correction given at a particular time will affect the intercept two or three minutes later. Most importantly, students cannot be shown the relationship between two-dimensional intercept geometry and the fact that aircraft are actually flying in a three-dimensional real world. The two dimensional radar display does not graphically show the effect of altitude separation on either intercept geometry or flight safety."

Real-time, interactive dynamic networks are used to simulate the real world in man-in-the-loop training paradigms and to facilitate remote control of vehicles, weapons, and other control structures (e.g., mechanical "arms"). They provide a context from which the spatial and temporal features of objects and events can be easily interpreted. Real-time dynamic networks can be used to convey interactive events, such as those governing the cooperative operations among aircraft in a flight squadron (tactical) or tanks in a platoon (strategic).

A three-dimensional data structure can also be used to scale abstract attributes just as easily as the physical attributes discussed in Section 2.2.1. Examples of abstract attributes might include: importance, urgency, and difficulty. An integrated assessment of these types of attributes can be represented by multidimensional scaling techniques where the similarity among pairs of items are measured and described as an arrangement of the items in a multidimensional space. Moreover, the dimensions of the resulting space can be used to make inferences about the basis of subjects' similarity ratings. Three-dimensional scaling of abstract attributes would be beneficial for applications such as time management, task structuring, and mission planning.

2.2.2.2 Data Representation in Memory

Three-dimensional displays can facilitate information retention and retrieval. Evidence exists for analog representation of information in memory. Analog memory codes represent information that seems continuous or has properties that are similar to actual perception (i.e., imagery). For example, even when patterns are represented as 2D drawings, subjects perceive the patterns as 3D objects and can mentally "rotate" them in different planes. The organization of the elements composing the analog memory code, however, appears to be an important factor in how well analog information is retrieved from memory. That is, people are better at remembering meaningful, integrated pictures than disorganized, non-related pictures.

Generally speaking, pictures are more easily recognized and can be more easily discriminated from one another than words. In one study, subjects were asked to repeatedly try to recall items from a list. When the items had been presented as a list of words, average recall performance was fairly constant after the first hour. When the items were presented as pictures, however, recall performance continued to improve for about four days.

A number of studies have shown that people have a vast capacity for storing visual details. In these studies, subjects were able to recognize 600 previously viewed pictures or 2560 previously viewed images with 97 and 90 percent accuracy, respectively. This capacity is far greater than the ability to recognize previously viewed words. This type of data indicates that a specialized code for visual information might be available for Long Term Memory (LTM).

If visual information in LTM is encoded to preserve the physical attributes of the visual stimulus, then it would be expected that 3D displays would have the advantage of representing these physical attributes directly in the image or picture presented to the viewer. Studies have shown that when meaningful, integrated pictures or images are used to represent information, recall for the location and identity of objects is very good. Therefore, 3D imagery or pictorial formats might be very beneficial to the recognition of significant objects (e.g., targets, threats, way points) and to the display of spatially distributed resources (e.g., stores, weapons).

There is also a variety of evidence that imagery influences memory performance and that imagery is a very effective mnemonic strategy. It appears that several aspects of the encoding task, including context, generally influence the retrieval of information. Mnemonic techniques provide an integrated context by which information can be represented in memory. This context serves as a set of potential retrieval cues. A well known mnemonic strategy, referred to as the "method of loci," works through spatial imagery and is very effective. These types of strategies are compatible with 3D representation of information and would be beneficial for facilitating memory, especially memory for spatial information (e.g., briefings, intelligence information).

2.2.2.3 Anticipation/Expectation

There is evidence that expectancy can influence perception (e.g., recognition of degraded pictures) and judgment through context effects and inference cueing. The term "inference cueing" is used to describe the effects of preview and prediction. That is, displaying a preview of expected events, actions or conditions serves to bound the inferences the viewer might make with respect to his/her own actions.

For example, a pictorial representation of the safest route for a tactical pilot to fly during a particular mission phase constrains the pilot to certain flight control actions. The objective and benefit of this "pathway in the sky" flight path indicator is to reduce the information load on the pilot by eliminating costly time spent in gathering information traditionally distributed throughout the cockpit. Disparate data are integrated into synthesized, higher level display variables that are directly relevant to the pilot's decision making process.

Representation of task loading is another application for 3D displays. In situations where task management is important, tasks that need to be performed can be displayed within a 3D structure where depth can be used as an indicator of task load, task priority, etc. Three-dimensional representation of information might also be beneficial for predictive flight control displays and for indicating potential threat conditions.

More abstract data is beginning to benefit from advances in the new area of data visualization as well. Scientists studying overwhelming volumes of sensor readings from interplanetary satellites, for example, may be able to gain important new insights into the meaning and pattern of raw data given the capability of displaying it graphically in three dimensions.

3.0 3D IN C3I APPLICATIONS

The primary purpose of this study was the analysis of a subset of typical C3I battle management applications and the subsequent evaluation of the ways in which three dimensional display technology could aid in the accomplishment of mission tasks. One part of this analysis included developing an understanding of possible applications which rely upon data that would, theoretically, lend itself to a three dimensional representation. A discussion of this analysis is provided below in Section 3.1. Another part of the study sought to identify specific unique benefits that might result from the 3D display of information. The results derived from a technology-independent examination of information utilized in the course of battle management activities are discussed in Section 3.2. The fundamental reason for conducting this study was to provide some insights into which battle management tasks should see an improvement in performance as a direct result of the use of 3D display capabilities. Section 3.3 maps the benefits of Section 3.2 to specific battle management applications which possess the characteristics described in Section 3.1.

3.1 Candidate Applications and Data Types

3.1.1 Inherently 3D Applications

The first type of data that is considered suitable for representation in three dimensions is data with inherent 3D characteristics. This includes both data portraying spatially related objects such as terrain, surface features and entities, aircraft, and satellites as well as data with a spatial component like sensor coverage.

3.1.1.1 Object Representation

Three classes of objects are candidates for representation. Natural objects like terrain, vegetation and water can be used to provide a compelling and, in some cases, relatively unchanging spatial environment in which other activities take place, while naturally occurring events like weather conditions and natural lighting may be of interest as well. Man-made objects, to include moving vehicles (land, air, sea, space), stationary features like towns and electronic envelopes such as radar threat domes are imposed on a natural environment and represent the objects of greatest interest in C^3I applications. The final class of object is text. In addition to the graphical representation of an object or entity, text is necessary for providing the appropriate descriptive information associated with it, information that cannot be represented pictorially.

Data representing natural feature information is often readily available in a form that can be used to generate 3D views. One problem with representing natural scenes, however, is that of scale. While the capability exists to display large amounts of terrain or space, the relative size of human scale objects within that space can become miniscule. Similarly, as a larger area of terrain is viewed, the vertical relief diminishes. This effect can be offset to some extent by changing the scale of objects in the scene, exaggerating the vertical dimension or replacing objects with representational icons. The result, however, may be a loss of accuracy or confusion as to the actual scale of objects in the scene.

Man-made objects representing fixed cultural features are subject to many of the same considerations as natural features. Mobile objects present unique opportunities and challenges in a 3D environment. Many of the issues of concern in the C^3I arena deal with the interactions between moving objects. Allied and enemy ground forces, air defense activities, locations of targets and threats all provide inputs to a dynamically changing scenario. Motion in a three dimensional space provides an added component to the viewer's perception of the situation. In addition to supplying valuable monocular motion parallax cues, motion in three-space can allow the viewer to more accurately perceive acceleration and gauge the time at which an object will reach a specific point in space. The capabilities afforded by movement in 3D can be very important for both the mission planner objectively considering the interaction of a number of objects and the trainee subjectively experiencing simulated encounters in close air support, intercept or reconnaissance scenarios. Data describing events not normally visible to the human eye can also be plotted in a 3D environment. A 3D volume with a density gradient illustrating the effectiveness of radar coverage for a particular site is an example of valuable information rendered graphically.

The display of text is a vital component of many battle management activities. Detailed descriptive information that cannot be graphically illustrated must be available upon command. Some problems with text, particularly in conjunction with a graphic display, are that it cannot be displayed over other text, only small amounts can be displayed without cluttering the screen, yet it must be displayed large enough to be read. When text associated with several objects on the screen must be displayed, it is difficult to ensure that the correspondence between text and object is obvious while maintaining readability. In a 3D environment, some measure of relief can be achieved by displaying the text at different depths. Decluttering in this way relieves the viewer of the need to discriminate between textual messages displayed in the same plane and facilitates the association of text with objects at different depths. This capability is enhanced by the judicious use of shading and scaling to preserve readability while providing additional monocular depth cues.

3.1.1.2 Spatial Viewpoints

While manipulation of a 2D display to show a scene from various viewpoints can provide the viewer with a sense of relative locations of objects, similar manipulation of the viewpoint in a three dimensional display system allows the user to perceive the environment from a selected position in three-space. This means that the viewer, from a single selected point of view, can determine the relative distance of objects within the field of view. With magnification (zoom) and pan capabilities, a more realistic assessment of the situation can be achieved in a shorter period of time, improving the performance of such tasks as route planning, tactical simulation and training.

3.1.1.3 Object Manipulation in Spatial Context

With the ability to create objects in a three dimensional space and to view them from any desired location in that space, the manipulation of those objects allows the user to create dynamic situations, observe object interactions and evaluate the consequences. In a 3D environment, rapid placement and orientation of objects enables the operator to more easily construct a scenario with the desired characteristics and improves the speed with which he can perform this task. It allows for easy definition of otherwise difficult data such as flight paths or deployment patterns and supports rapid testing of what-if conjectures. A significant technological limitation in this area, however, is the lack of proven input devices and user interface techniques for use with 3D displays. Until the technology improves, this will remain one of the primary restrictions to full user interaction with and acceptance of 3D display systems.

3.1.1.4 Volumes and Envelopes

As mentioned briefly above, a three dimensional viewing space can be effectively used to display volumes representing radar coverage or similar sensor data. Other data appropriate for representation would include direct fire weapon effectiveness, likelihood of detection, regions under control of specific combat units and anticipated ECM activity.

In mission planning, for example, detectability is a composite estimate of the range, sensitivity, and scope of the enemy's detection system, e.g., radar, and the effectiveness of the detection-evasion strategy of the weapon system platform. Terrain might be a major consideration in determining the scope of the enemy's detection system. For example, radar shadows might exist on the leeward side of mountains, thereby reducing the scope of detection. From an analysis of all of these factors, one could generate volumetric representations of the probability of detection by the enemy's radar.

Placement of the radar unit, its power, and the characteristics of adjacent terrain all affect the shape of the detection canopy surrounding each radar installation. Because of terrain shadowing, the probability canopies will not have symmetrical spherical fronts. Thus the intersections of iso-detection probability fronts from adjacent radar installations may not describe circles, and the volume described by their union may be irregular.

Similar considerations apply to the enemy's threat capability. The placement, range, accuracy, and scope of the enemy's weapon systems can be used to develop three-dimensional potential threat volumes along alternative flight paths to the target. The intersections of threat-potential fronts can be used to predict loci of maximum permissible threat consistent with mission objectives. These loci will not be planar, so their depiction on a 2D display may be difficult to interpret. Interpretation should be greatly facilitated by the 3D presentation of the iso-threat loci.

Ideally, a 3D display might present a three-dimensional rendition of the terrain along alternate flight paths, as well as ghosted views of both the detection fronts (at a predetermined detection probability) and the threat fronts (likewise at a predetermined tolerable threat potential.) It may be necessary to encode detection and threat fronts differentially, e.g., by color, so that the viewer can assess locations in three-space that present the best compromise. For example, there may be altitudes at particular map coordinates where the threat potential exceeds the tolerance threshold, but the probability of detection at this location is very low.

To maximize the benefit from the displayed information, the viewer might synthesize a perceptual volume surrounding the aircraft which shows the location of the predetermined threshold values of the threat and detection variables. The viewer might also have the ability to select other values of each variable so that he can assess the joint probability of detection and threat at any displayed location. Decisions can then be based on whether the proposed flight path pierces the detection and threat fronts, where piercing the front means exceeding the present value.

3.1.2 Other 3D Representations

In addition to the data described above which possesses inherent spatial characteristics, certain forms of data that do not possess such obvious spatial features can benefit from a three dimensional representation as well. The growing field of data visualization provides an indication of the widespread interest in finding new and flexible means for displaying and examining information. Applications for data visualization tools range from debugging large amounts of unprocessed data and determining the most promising directions for research to extracting and effectively presenting previously undetected relationships among the data. Three dimensional displays provide the user with an additional axis along which information can be plotted. Some basic examples of applications in the C^3I environment are discussed below. Other possibilities for presenting information in a three dimensional environment are primarily restricted by the imaginations of the researcher, the software developer and the end-user. For professionals trained and experienced in preparing data for display in two dimensions, making effective use of spatial display capabilities can present a substantial creative and technical challenge.

3.1.2.1 Networks

A form of data representation that can be enhanced by 3D is the network. The addition of depth allows for the display of more complex systems and relationships than a 2D rendition. Some examples include communications nets to illustrate who communicates with whom as a function of mission scenario and time, and dynamic networks for training purposes (as described in Section 2.2.2.1) in which the network shows the relationships between complex sets of variables, such as the effect of the timing of a turn in a particular fighter aircraft on the geometry of the target intercept. Another form of network displays are management charts showing organizational structure and PERT charts for purposes of tactical and logistics planning and assessment.

3.1.2.2 User Interface

The field of man-machine interfaces has several possible applications areas for 3D technology. Multiple spatial displays can exist at different depth planes, in contrast to the current technique of multiple windows as an analogy to a desktop. Three dimensional menuing systems could facilitate the selection of interrelated options. A spatial hypermedia facility would allow for rapid progression through linked spatial displays along some line of interest to the user. The implementation issues associated with these concepts are essentially extensions of existing display management and information retrieval issues encountered in developing 2D systems.

3.2 Tentative Benefits to Battle Management

In examining the unique benefits that a three dimensional display capability offers battle management applications, it was necessary first to consider the capabilities offered by more conventional, perspective 2D technology or 2 1/2 D. One conclusion reached during this process was that perspective 2D capabilities are often not fully exploited. As hardware costs drop and processing speed increases, the display capabilities of graphics workstations continue to expand tremendously. With the ability to manipulate scenes and move within the 2 1/2 D environment, perspective displays can rival some features of 3D displays without imposing the computational demands required for spatial image generation. To some extent, this increasing availability of good perspective graphics has probably had the effect of limiting the aggressive development of 3D technology. Until technological advances and user experience allow the appropriate applications areas for 3D displays to be more clearly defined, perspective 2D technology applied with creativity and innovation can and will continue to meet the needs of many applications.

Three tentative benefits resulting from the use of 3D displays in battle management applications were identified during the course of the study. These benefits were derived from a technology-independent examination of information utilized in the course of battle management activities. They are:

- decluttering
- the display of irregular volumes
- the display of three dimensional scenes over time

Artificial limitations are imposed on the presentation of information via computer monitors as a result of the size of the screen, the resolution of the image and the issues raised by displaying overlapping objects and text. The exponential increase in display space provided by the addition of a third dimension offers a means of resolving these display problems that restrict operational capabilities. Information presented at different depth planes declutters the image perceived by the viewer by reducing the data presented in any one plane and allowing him to selectively focus on it without distraction.

In addition to providing a way to separate individual objects spatially, the 3D display of information enables the viewer to perceive three dimensional objects as possessing depth themselves. The form of regular, geometrically shaped volumes can be inferred from perspective representations. Irregularly shaped volumes, however, such as those depicting realistic electronic sensitivity or projection envelopes, cannot be adequately perceived by viewing the image on a two dimensional surface. Similarly, the intersection of multiple volumes is most likely not planar, and depiction as a planar form is both misleading and inaccurate. A major benefit of 3D displays is their capability to provide, in a form detectable to the viewer, information as volumes as opposed to information as planar areas. This increased quantity of information, and the complex forms it can take when volumes intersect, can only be perceived in a three dimensional display environment.

The final advantage of 3D displays involves the movement of the objects and volumes described above. This essentially allows the viewer to perceive a fourth dimension, that of time. A three dimensional display space not only allows for the display of object in space, but for their movement in space as well. The ability to perceive relative motion in three dimensions results in a more rapid and accurate estimation of speed, velocity and time at which an object will reach a certain point in space or intercept another object. The display of this information on a two dimensional screen is very difficult to accomplish.

3.3 Specific Battle Management Applications

In discussions regarding the C3I scope of the study, RADC and the team agreed that attention should be focused primarily on the functions of situation assessment and operational mission planning in an immediate post-hostilities timeframe. This section identifies aspects of these functions that would seem to benefit the most from 3D advantages described above.

3.3.1 Situation Assessment

Situation assessment as a function of C3I includes maintaining information on the status of a variety of factors: friendly and allied forces (air, ground, naval); enemy forces (same as for friendly and allied plus threat assessment); the battlefield (combat assessment); and other dynamics of the battlefield such as logistics, environmental factors, non-combatants and obstacles. Most of these situation assessment functions involve the positions, conditions, activities and capabilities of man-made and natural entities within a very well defined physical space and, hence, lend themselves to representation in a 3D display environment. The use of 3D for a static display of forces and related information could provide benefits in terms of decluttering the displayed image, but in most cases represents an increased overhead cost with no substantial improvement over current practices. Greater benefits are realized by the more active use of the display medium.

Two fundamental opportunities exist to use the 3D display environment to exhibit the motion of forces. The first of these illustrates the historical movement of military and natural forces within the geographic area of interest. Much of the information maintained as part of the situation assessment function is fixed (though not always known) at any given time. A display of the movement of entities that led to the current situation would indicate the direction and force of tactical thrusts. Presented in 3D, the display could provide insights into the effect of terrain on movement. In illustrating movement of air and naval forces, the 3D display could be particularly effective in imparting a sense of distance between forces moving in three dimensional space. The second use of motion in situation assessment involves monitoring indications and warning factors by projecting force movement into the relatively near future to determine possible consequences of current activity. Closely coupled with this application is the monitoring of environmental and other dynamic factors of the battlefield to project their effect on the current and anticipated states of the battlefield.

More appropriate to situation assessment activities is the ability of 3D to provide a more accurate view of spatial volumes and their intersections. The status information of all military forces includes details of electronic warfare characteristics such as coverage, effective radiated power, collection radius of sensors and SIGINT systems, and vulnerability to countermeasures. Other data that can be represented by volumes or envelopes includes weather and contamination data. The usefulness of 3D in viewing data that is inherently spatial in nature is that it provides a more complete and realistic perception of the relative sizes and positions of the various entities, particularly as they interact over time.

In summary, the applications associated with C3I situation assessment that would appear to benefit the most from the use of 3D displays are those which support a combination of dynamic display techniques, i.e., movement over time and the representation of data by volumes. The display of the battlefield situation as perceived over time, illustrating appropriate data volumetrically, would take maximum advantage of the anticipated benefits of 3D displays. Perhaps less beneficial but more widely applicable would be the use of 3D to indicate necessary status information. The ability to overlay on the battlefield area map status information, be it inherently spatial information such as line-of-sight for indirect fire weapons or more abstract information like mission effectiveness and damage assessment, is a useful and identifiable capability improved by 3D displays. More advanced data visualization techniques may offer other possibilities as well.

3.3.2 Operational Mission Planning

Operational mission planning seeks to devise and accomplish tactical missions in support of the more strategic goals determined during the battle planning stage. In contrast to situation assessment, which strives to determine the state of many aspects of the battlefield at any given time, mission planning attempts to determine the likely results of many possible and interrelated courses of action. Facets of operational mission planning include target system development in which targets are defined and categorized, targeteering for identifying the target, weapon allocation for the mission, weapon application and evaluation, FRAG order production and plan analysis comparing predicted effectiveness with its cost. Development and evaluation of plans requires the ability to simulate their execution and examine their performance at many stages. The ability to change aspects of the modeled plan in response to perceived threats provides the user with a "what-if" flexibility for developing the most effective plan. The activities and requirements of the mission planning function map very well to the data types and anticipated benefits described above.

The most obvious use of 3D technology in operational mission planning is the visual modeling of mission execution from a mission planner's viewpoint. 3D can provide the spatial image of the appropriate area of interest. Conventional graphics handling routines supply the algorithms necessary in most cases for manipulation of the spatial image (i.e., rotation, magnification) while supporting manipulation of objects within the image (redirection of forces, etc.). Because viewing the execution of the proposed mission over some period of time is critical to the planner, the motion of objects and their interaction with volumes in 3D can provide a real benefit.

The simulation of mission execution can be viewed from another perspective as well, that of the mission pilot. Targets may be fixed or mobile, point targets or an area. Battlefield conditions will vary depending on time of day, time of year, weather and the combat situation. To improve target identification and provide some advanced insights into conditions affecting the mission, a pilot's eye view of the mission can be displayed and can be used to explore the effects of various tactical moves and responses in the execution of the mission. Many of the options available in the mission planner's view of the scene would be appropriate to the pilot's view as well. Being able to 'see' the radar detection envelope for a specific probability of detection would be very useful as the aircraft moves around it, for example. The pilot's view of the scene is, however, on a significantly different scale from the mission planner's. Objects are closer and distances between them are more clearly perceived. Where the planner views the aircraft and threat envelope from a distance, the pilot sees the surface of the volume closing in as he approaches it. Because of these features, this application is a particularly strong candidate for enhancement by 3D display technology.

4.0 3D DISPLAY TECHNIQUES

This section examines a variety of existing three dimensional display techniques for their utility in the C3I arena of applications. Because each technology has different features and drawbacks that determine its applicability to particular tasks, technology-specific viewing factors are discussed as they apply to each technique. These factors may include the ease of fusion of stereo images, binocular rivalry, flicker, pseudoscopic zones, and the presumed or demonstrated propensity to induce visual fatigue.

In addition to parameters associated with the display techniques, the discussions will include an examination of several features considered important or desirable to C3I battle management applications. These factors include image resolution, color, real-time display capability, full parallax, multi-viewer support and the requirement for user-worn aids. Image resolution addresses the degree of detail that can be viewed on the display. Depending upon the technology used, the availability of adequate resolution and the prospect for increasing resolution may be issues of concern. Color is a highly desirable feature because it provides both an added realism to graphic images and an additional dimension for indicating information. A real-time display capability is essential for C3I applications. While less dynamic display requirements may be sufficient for some disciplines, battle management is characterized by its need for immediate and projected status information in a highly volatile environment. Full parallax means that as the viewer moves his head to the right, for example, he is able to see more of the right side of a viewed object. The effect is the same as rotating the object to the left. Viewer-induced head motion parallax allows the viewer to perceive additional information in a very natural manner. Display systems that lack this feature can provide confusing viewing cues to the user by making it appear that a viewed object rotates to the right as the viewer moves his head to the right. The ability for a displayed image to be perceived clearly by multiple viewers is important in battle management situations where the displayed image provides information for evaluation and discussion by several people. Two components comprise this requirement: the need for the generated image to be viewable from different positions relative to the display and the need for the perception of the image to be relatively independent of viewer variability. Finally, for the applications within the scope of this report, the need for the viewer to wear glasses or other aids is generally considered to be an undesirable restriction.

4.1 Stereoscopic Techniques

Stereoscopic techniques involve the presentation of two slightly offset images of a view to each of the viewer's eyes. The offset duplicates the different perspective views of the two eyes, providing a perception of binocular depth. The problem associated with providing stereoscopic views is the manner in which the visual access to each eye is restricted to the appropriate image. Section 4.1.1 reviews techniques in which the images are separated by the viewer, often through the use of viewer-worn glasses. Section 4.1.2 examines several techniques which separate the image at the display source. Many of these systems are autostereoscopic, meaning they do not require user-worn aids for the perception of depth via stereopsis.

4.1.1 Viewer Separation of Images

4.1.1.1 Chromostereoscopic

All types of chromostereoscopic (or color stereoscopic) display systems rely on chromatic aberration to provide the impression of depth. Most human eyes have a small amount of chromatic aberration caused by the displacement of the visual axis (the line of sight) from the optic axis (the line normal to the cornea and lens of the eye). Because the magnitude of aberration varies with wavelength, light of some colors is refracted more than light of other colors. For example, when two juxtaposed points of light, one red and one blue, are viewed with the left eye, they will be seen as separated from each other; the red light will appear to be to the left of the blue light. When they are viewed with the right eye, the red light will be refracted to the right of the blue light. As a result, when the lights are viewed with both eyes, they will be imaged with binocular disparity. This disparity will make the red light appear closer to the observer than the blue light, even though they are physically the same distance from the viewer. Display systems based on chromostereopsis have the advantage of requiring a single display surface, such as a CRT or dichroic LCD, which can be viewed by several viewers simultaneously. This type of stereo display, however, exhibits a number of fundamental limitations.

Chromostereoscopic displays suffer the disadvantage of requiring stimuli that are to appear in different planes to be appropriately colored. Where the three-dimensional scene to be imaged is composed of chromatic objects, chromostereopsis may produce depth cues that conflict with real depth cues like perspective and parallax. Furthermore, the angle between the visual and optic axes varies widely among people, leading to a wide range of perceived depth planes across observers for the same physical stimulus. Some observers even see the chromatic stimuli in the opposite depth relationship, i.e. blue closer than red.

There are two particular forms of color stereoscopic systems that merit identification. Stenopeic displays enhance depth resolution by artificially displacing the observer's visual axes. This displacement is produced by a pair of stenopeic glasses that force the observer to view the display surface through a pair of pinholes that have been positioned in otherwise opaque masks so as to separate the two visual axes. This increases the separation of the optic and visual axes, thereby enhancing the chromostereoscopic effect. The glasses dramatically reduce the observer's field of view and promote rapid visual fatigue.

The second form of chromostereoscopic display is the prismatic type, which has somewhat fewer disadvantages than the stenopeic type although it still requires the viewer to wear spectacles. In this implementation, the effect is enhanced by prisms worn in front of the eyes. The prisms increase dispersion of the incident chromatic rays, resulting in increased binocular disparity and, therefore, perceived depth. By using adjustable prisms, such as Risley prisms, it is possible to vary the depth resolution and to standardize the perceived depth across observers. However, even the simple prism spectacles are cumbersome and presumably would promote rapid visual fatigue due to the phorias they induce.

In terms of applicability to C3I, chromostereoscopic systems suffer from their inability to support full color and the need in some instances for the viewer to wear cumbersome glasses. In addition, although the display surface can be viewed by multiple viewers, the technique is so sensitive to differences in observer-specific vision characteristics as to be considered unreliable at best. The technique itself imposes no constraints on resolution, but its use in the real time depiction of motion would require a constant and distracting shift in the colors of individual objects as their positions changed. Full parallax is not preserved in this system. In summary, the technique is neither dynamic nor robust enough for C3I applications.

4.1.1.2 Pulfrich Phenomenon

When the luminance of binocular images is different in the two eyes, the processing time for each image differs by several milliseconds. With static images this has no perceptual effect, but with dynamic images it induces an illusion of curvature in the pathways of moving objects. An object moving in a straight line across the observer's field of view at right angles to his line of sight appears to move in an arc. When the image in the left eye is of lower luminance than that in the right, objects moving to the right appear to move through an arc that is convex to the observer. Thus, an object moving back and forth, such as a pendulum, would appear to be describing an elliptical or even circular path.

Stereo displays based upon the Pulfrich phenomenon have several disadvantages that make them impractical for most applications. The most severe limitation is that they only produce an impression of motion-in-depth rather than an impression of depth, per se. In addition, these displays require that the direction of fronto-parallel motion in the image be controlled in order to produce motion in depth of the intended polarity. That is, depending upon which eye is viewing the dimmer image, motion from left to right will always follow a convex (or concave) path while motion in the other direction will always be the opposite. This obviously reduces the operational value of the technique in applications where motion may occur in many directions and where depth perception is desirable even in the absence of motion. Pulfrich-based systems also require that one of the binocular images be of a lower luminance than the other, which is most easily accomplished by having an observer wear a neutral density filter (one that reduces the intensity of the image without changing its color) in front of one eye. This required difference in luminance tends to produce binocular rivalry and visual fatigue, though color and resolution do not themselves suffer as result. User-worn aids are required, often in the form of passive eyeglasses. Multiple viewers can perceive the sense of depth from a single display. Like the chromostereoscopic systems, the fundamental limitations imposed on control of the image render this technique inappropriate for battle management applications.

4.1.1.3 Color Anaglyph

Color anaglyphs separate pairs by color subtraction. Two perspective images of the same three dimensional scene are presented simultaneously on the display screen. The disparate regions of one image are encoded in short wavelength light, and those of the other image in long wavelength light. Where there is no image disparity, the stereo pair can be encoded in full color. The viewer wears spectacles comprising one short-wavelength lens and one long-wavelength lens. Each lens selectively transmits significantly more of one of the stereo images, thereby effecting monocular-image separation. However, because each spectacle lens must transmit light from the entire spectrum in order for the viewer to perceive full-color stereoscopic images, the optical density of each lens cannot be very great. That is, each lens must not be too dark or transmit too narrow a range of the visible spectrum. This produces annoying cross-talk between the left and right eye-channels, which is perceived as ghost images.

This is an old technology that lends itself to both static and dynamic displays. It has been used to produce 3-D comic books and 3-D motion pictures. A 3-D television system has also been based on color anaglyphs. In this embodiment, the amount of disparity is greatly reduced, relative to that used in cinema and hard copy. This produces a full-color image that can be viewed with or without the color-anaglyphic spectacles. When the spectacles are not worn, the color TV image has some blurry color fringes adjacent to three-dimensional objects, but because the amount of disparity has been kept to a minimum, the color fringes are not a severe detriment to image quality. Also, the width of the fringes is greatest in objects that have the greatest depth, but due to the visual system's limited depth of field, these objects are normally perceived as blurry. When the spectacles are worn, the viewer perceives a stereoscopic image of the scene presented on the screen because of the binocular disparity encoded in the color fringes.

Image separation by the color anaglyph method produces some undesirable phenomena. Because it is impossible to balance the transmission of the long- and short-wavelength lenses for all combinations of viewer and display, there is frequently a difference in effective optical density between the left- and right-eye lenses. This tends to produce both binocular rivalry and the Pulfrich phenomenon, as well as visual fatigue.

The blurring of the image reduces the functional resolution of the image. Color and real-time processing are both largely supported, though some flexibility in the use of color is necessarily sacrificed to produce stereo images. Multiple viewers can share a display, though the system is somewhat sensitive to viewer variability. Glasses are required for 3D use, but the viewer can operate in 2D without them. Full parallax is not maintained. In spite of its use in feature length motion pictures, 3D based on color anaglyph is only marginally effective and too visually fatiguing for long term use in battle management.

4.1.1.4 Polarization Stereogram

More a technique for achieving binocular image separation than a display type per se, the polarization stereogram is possibly the most common. In contrast to chromostereoscopic and Pulfrich phenomenon-based techniques which rely on side effects of human vision (and consequently suffer from its variability), the polarization stereogram presents two different perspective views to the viewer in much the same manner as the color anaglyph method. However, the use of polarized rather than colored filters provides for more effective image separation while not affecting the color of the scene. Each eye views the display surface through a polarizer that is orthogonal to its partner. The polarizers separate the left- and right-eye images that are presented on the display screen simultaneously or alternately at a rate above flicker fusion. Two forms of polarization can be used for this display type: linear polarization and circular polarization.

In most applications, the viewer wears spectacles that incorporate polarizers that must remain orthogonal to their companion polarizers at the display surface. Cross-talk occurs for several reasons. Crossed polarizers are not perfect attenuators: they exhibit wavelength-dependent extinction characteristics. Furthermore, in some applications the polarizers are positioned by the attitude of the viewer's head and tilting the head reduces the maximum possible extinction. (Extinction varies as the square of the cosine of the angle between the polarization axes of the display and spectacle polarizers.) Thus, if a viewer tilts his head, some of the right-eye signal will be seen by the left eye and vice versa, thereby producing annoying "ghost images." In systems utilizing circularly polarized filters, this problem is eliminated.

Both projection and direct-viewing applications have been developed, the most common projection application being 3-D motion pictures. Projection systems must be based upon reflecting surfaces that do not significantly diminish the polarization of the left- and right-eye images. In one direct-viewing display system, a sector disk composed of alternating segments of orthogonal polarizers is positioned between the display screen and the viewer. This sector disk is rotated synchronously with the field rate of the display so that alternate fields are viewed by the two eyes. This application has the disadvantage of producing a variable extinction ratio of the binocular images by requiring that the polarizers rotate into position in front of the display screen. Cross-talk is relatively high in this type of display.

The polarization stereogram technique of image separation imposes no constraints on the resolution, color, speed, or number of viewers, though brightness of the displayed image is reduced significantly by the addition of the filter. As in other stereo systems, full parallax is not maintained, and the system requires the user to wear spectacles. Because of its relative independence from the display medium, the technique can provide added capability to existing systems. For computer displays, the burden levied on the computer system is essentially that of doubling the number of displayed images and the computations to create them. Considerations for applications involving real-time displays are addressed in the section on Field Sequential techniques.

4.1.1.5 Field Sequential

Stereo displays based on field sequential television technology have been developing rapidly during the last several years. This technology presents left-eye and right-eye views alternately on the TV screen and permits each eye to see its own view. Broadcast TV lends itself readily to this type of display because of the way in which the image is written to the screen. Broadcast TV presents 30 frames per second, with each frame consisting of two interlaced fields of scan lines. The first field consists of the odd-numbered scan lines and the second field consists of the even-numbered. Thus, it is possible to present both eye views in each frame by making the first field the left eye view and the second field the right eye view.

The problem then becomes one of image separation, which resolves itself to one of synchronizing left- and right-eye masks to the field rate of the TV. Numerous methods have been developed for accomplishing this image separation, but they all suffer from several failings. Chief among these are flicker and cross-talk. Although the standard TV frame rate is 30 Hz, the interlaced field rate is 60 Hz. In field sequential stereoscopic TV, each eye sees only one field, so its effective rate is only half that of the normal TV field rate, i.e. 30 Hz. Alternation at 30 Hz can produce annoying flicker. One solution is to double the usual frame rate to 60 Hz, that is, to produce a 60 Hz noninterlaced system or by developing a 120 Hz field-rate monitor. The monocular frame rate will then be 60 Hz, but the resultant technology does not comply with NTSC TV standards.

The other major problem is cross-talk between the left-eye and right-eye images. One source of cross-talk is the persistence of the phosphors that form the image. If the phosphors cannot be switched off quickly enough, some of the left-eye image may still be visible on the screen when the right-eye shutter is opened. This is not as pronounced a problem with 60 Hz television, but it is a consideration in 120 Hz monitors.

Field sequential TV displays have another characteristic that detracts from the veracity of their stereoscopic image quality, one is that is shared by other technologies that separate monocular images artificially. When the viewer moves laterally with respect to the display screen, the motion parallax induced by this movement is opposite that which would occur if the viewer moved while examining a real three-dimensional object. When examining a real 3-D object, a rightward movement would produce an apparent leftward movement of the object, i.e. more of the right side of the object would be exposed. However, rightward movement of the viewer does not expose more of the right side of the synthesized stereoscopic object, and the visual system interprets this as corresponding rightward movement of the displayed object. Thus, motion parallax produced by viewer movement is of the wrong polarity, which can be a source of annoyance.

Two major types of field sequential TV are recognized: those that have the active image-separation element at the image source, and those in which active separation is accomplished at the viewer. Both types utilize the polarization technique described above. Both require that the viewer wear spectacles, but the latter has the additional requirement that the viewer's spectacles be linked to the display, usually by wires.

When the monocular images are separated at the source, i.e. at the display, the viewer need only wear passive polarizer spectacles. The TV screen is viewed through an electro-optic system, such as a Lead-Lanthanum-Zirconium-Titanate (PLZT) shutter. Part of the PLZT shutter, which incorporates a plane polarizer and the PLZT crystal, is positioned just in front of the TV screen. When an electrical potential is impressed across the PLZT crystal, it rotates the plane of polarization of an incident light very rapidly through 90 degrees. If a polarizer of the same orientation as that near the TV screen is worn over the right eye, then the right eye will receive light from the screen when the PLZT crystal is in the ground state, but it will not receive light from the screen when the PLZT crystal is excited.

Conversely, if a polarizer orthogonal to that near the TV screen is worn over the left eye, then the left eye will receive light from the screen only when the PLZT crystal is in the excited state. By synchronizing the excitation of the PLZT crystal to the two fields of each TV frame, it is possible to present one field of scan lines to the left eye and the other field to the right eye. If the images produced by the scan lines are two perspective images of the same object, it is possible to produce a stereoscopic image of that object.

This type of field-separation system has the advantage of requiring that the viewer wear only passive elements of the PLZT shutter system, i.e. orthogonal plane polarizing spectacles. The currently available Tektronix system adds about $12,000 to the cost of a graphics workstation.

The second type of field-separation system mounts the entire PLZT shutter system on the viewer. Each spectacle consists of a sandwich of crossed polarizers with PLZT crystal filling. The principle of operation is the same as that described above, but this embodiment of field sequential TV suffers the disadvantages of requiring a wire link to the viewer and a separate PLZT shutter system for each viewer. Several Japanese companies sell inexpensive versions of this system, and one offers a 3-D camcorder for about $2000.

As discussed above, the polarization stereogram method adds a stereo capability to an existing display system. Equipment is commercially available that can adapt high performance computer graphics displays to stereo field sequential devices. Given sufficient computational capabilities, any battle management application suitable for computer display can enjoy the added benefit of stereo at the cost of some image brightness, possible bleed through of images, and lack of full motion parallax. For situation assessment activities, these drawbacks are not a major problem. However, the potential for visual fatigue and the need to wear passive glasses for stereo viewing would be a persistent cause of user annoyance. In mission planning applications, the capabilities provided by 3D could be particularly impressive. The most serious problem, however, might prove to be the polarity of motion parallax. While systems presenting the planner's view of the battlefield might not be significantly affected, the utility of those portraying the pilot's view would suffer markedly. However, until further human factors research is performed on stereo systems, the actual extent of their utility versus difficulty of use cannot be accurately gauged.

4.1.2 Source Separation of Images

4.1.2.1 Parallax Panoramagram

In this technology, several images of a scene, each taken from a slightly different perspective, are presented on the same display surface. Each eye is permitted to see only one image of the scene, that which is from its own perspective, and from these two disparate images the visual system synthesizes a perception of depth. Early examples of parallax panoramagrams used slit plates between the display plane and the viewer. The slits were aligned vertically and served to expose single images to each eye. The most common examples of static parallax panoramagrams are three-dimensional postcards. Several attempts at developing 3-D television used this technology. For C3I applications, this limits the number of viewers to one, and the position of the viewer's head is very important.

One advantage of parallax panoramagrams is that they are autostereoscopic, requiring no user-worn aids to impart a sense of depth. However, like many autostereoscopic displays, this technique can produce zones of stereoimagery separated by zones of pseudoscopic imagery. Pseudoscopic imagery occurs whenever the relationship of viewer, slit plate, and display screen causes the left eye to see the right-eye image and vice versa. This problem can be corrected by the use of "dead" or black zones between the left and right eye images. Another limitation of this technology is that the number of stereoscopic depth planes that can be produced depends on the number of images that can be displayed across the screen and successfully hidden by the slit plate. In the simplest examples, only three or four depth planes are produced. For still images captured photographically, this is not a problem. For dynamic computer images, however, this causes an apparent flattening of objects in the field of view, such that objects look like cardboard cutouts. Although resolution and color are not affected by the technique, the limitations on the depth of objects and limitations on viewing zones restrict its use in mission planning operations.

Finally, most parallax panoramagrams use one-dimensional image-separation elements and, hence, lack full motion parallax. As a viewer moves his head with respect to the display surface, the stereoscopic images do not occlude (reveal) previously visible (hidden) surfaces as occurs in true three-space. This is frequently interpreted by the visual system as in-phase movement of objects in the scene, so these objects appear to move in the same direction as the head movements. This can be an annoying artifact of parallax panoramagrams, as with the other systems already described.

4.1.2.2 Parallactiscope

The parallactiscope is essentially a temporal model of the parallax panoramagram, which uses a series of slits to ensure that each eye sees only its perspective view of a three-dimensional image. The system consists of a CRT on which are presented several perspective views of the same object and a moving slit that exposes sequential perspective views of that object. The CRT is synchronized with the moving slit so that the left eye only sees the object from its perspective, and likewise for the right eye. In one version, built by Homer Tilten of Arizona, the "slit" is a thin vertical strip of 1/4-wave plate that moves across the face of the CRT in front of a sheet of polarizing material. The viewer wears spectacles containing polarizers that are orthogonal to the polarizer in front of the screen. Thus, images on the face of the CRT are not perceived by the viewer except where the 1/4-wave plate renders them visible.

Due at least in part to the fact that the moving slit technology of the parallactiscope is mechanical, the effective frame rate of the device is slow enough to produce flicker. This could be eliminated by using electro-optical slits, such as liquid crystal or PLZT, but a more difficult problem to solve is the limitation imposed on the complexity of the displayed image by the requirement to produce sequential perspective images for both eyes. The greater the number of views, the better the perception of depth. However, as the effective frame rate increases, the time during which the perspective image can be generated decreases. At the moment, the system is limited to presenting relatively simple images such as 3-D waveforms and helical coils to a single viewer and does not provide full motion parallax. Even with technological advances in available bandwidth, the restrictive viewing zone severely restricts the application to battle management problems.

4.1.2.3 Lenticular Screen

To circumvent the technical problems involved in the development of ever finer slit plates, the lenticular screen was developed. In this technology, each eye is prohibited from viewing its partner's image by optical means rather than by occlusion. There are many different arrangements of lenticular screen displays but, in principle, they all operate in the same fashion. Like the slit plate, the lenticular screen must be positioned very precisely with respect to the multiple images on the display surface. When properly registered, the lenticular screen delimits the area of the display surface visible to each eye by refraction.

Because of the interocular distance, the line of sight from each eye intersects the same lens surface at a slightly different angle. This angular difference causes different parts of the display surface to be imaged in the two eyes, effecting binocular image separation. Like the slit plate technology, the lenticular screen type of display is limited by the number of images that can be successfully masked. Recent developments have permitted a much greater number of multiple representations to be presented, but the technology still suffers from the problems of viewer position and lack of motion parallax. At this point in their development, neither lenticular screen nor parallactiscope technology is robust enough to be fielded. Work is, however, continuing in both areas and the capabilities continue to expand.

4.1.2.4 Vertical Parallax

Vertical parallax can provide a compelling impression of depth, but by itself does not support stereopsis. It is mentioned here because of the recent development of technologies based on vertical parallax that purport to convey depth information. In the vertical parallax display system, two images of the same three-dimensional scene, each obtained from a slightly different vertical position, are presented sequentially. Like horizontal parallax, vertical parallax can selectively occlude or reveal features of a three-dimensional scene. When two images obtained from different elevations are presented alternately, features that are apparent in the image obtained from the higher elevation seem to disappear when the image obtained from the lower elevation is presented.

A 3-D TV system based upon vertical parallax, called Visidep, has been developed. It uses a pair of TV cameras mounted one above the other to produce images with vertical parallax. Initially, this system was designed to present the two images in alternation, one frame at a time, but that was found to produce too much flicker. Instead, a limited number of frames obtained from one camera are interlaced with those from the other camera. This reduces flicker, but it produces apparent vertical jumps of objects in the scene. The Visidep system is not a true stereoscopic display system, and its inherent image motion will probably constrain its use as a 3-D display system.

4.2 Volumetric Techniques

In contrast to stereoscopic systems which present two perspective views of a scene in a reconstruction of binocular vision, volumetric techniques attempt to create a three-dimensional image. Methods for doing this vary widely and have achieved some commercial success. Because of the spatial nature of their images, volumetric systems in many cases have the advantage over most stereo systems of being viewable by multiple observers without the need for user-worn aids. Section 4.2.1 describes various holographic techniques, Section 4.2.2 discusses varifocal mirrors, and Section 4.2.3 addresses several other systems.

4.2.1 Holograms

Holograms generally provide static rather than dynamic views which can be viewed by more than one observer and require no observer-worn image-separation hardware. Usually holographic images are monochromatic and rely only on differences in brightness to render images. Many holograms require laser reconstruction of photographic images, which renders them useless for real-time display and potentially dangerous, although safe low-wattage lasers will produce adequate holograms. Visual fatigue should not be a problem, as accommodation and convergence signals are not antagonistic while viewing holograms, and glare from competing ambient sources is not a problem. Because of their static nature and due to the processing required to create holographic images, their use in real-time battle management applications is not expected in the foreseeable future. Research is continuing, however, in many areas of holography. The brief descriptions of different holographic techniques provided below is intended to acquaint the reader with the diversity of methods being explored, describe some of their limitations and identify promising areas of interest.

4.2.1.1 White-Light Holograms

White-light or rainbow holograms, first developed by Stephen Benton (formerly of Polaroid Corporation and now at MIT), are static images that do not require laser light for reconstruction. The holograms are recorded by exposing only a thin vertical strip of photographic plate at a time. Inexpensive holograms can be made by either embossing mylar with a nickel holographic image or by the dichromatic method, in which transparent holograms are made from the original opaque image.

White-light holograms provide genuine horizontal parallax, but not vertical parallax. Thus, vertical movement of the observer produces perspective distortion. Furthermore, because these displays disperse white light in a manner similar to a diffraction grating, vertical motion also produces changes in chromaticity of the holographic image. Image resolution and contrast are both typically rather low.

4.2.1.2 Alcove Holograms

Alcove holograms are a recent development of the Media Labs at MIT. They comprise a concave 180-degree photographic film that produces a panoramic holographic stereogram. The viewer perceives the holographic object as being imaged in space beyond the cylindrical film surface. It is possible to design the alcove hologram so that stereoscopic objects appear to move as the viewer scans the surface of the film. The alcove hologram has many of the characteristics of the white-light hologram and, thus, shares many of its disadvantages. This technology shows promise for future development, but for the moment, development of this technology is proceeding slowly.

4.2.1.3 Multiplex Holograms

This is the commercial name for the embodiment of a type of hologram called the integral or Cross hologram [after Dr. Cross who was one of the first (with David Schmidt) to learn how to produce these holograms]. The Cross hologram is a cylinder that is illuminated from below with either white light or monochromatic light (different technologies). Recorded on the hologram are multiple images of an object taken at different times. If the object moved during the period when the multiple images were being recorded, the observer sees the object move as the cylinder is rotated. This technology is commercially available through a very limited number of suppliers, and at a cost considerably greater than white-light holograms.

4.2.1.4 Synthesized Holograms

Synthesized or computer-generated holograms may be the hard-copy of the future, but it is unlikely that they will constitute a major thrust in three-dimensional display technology. Current problems, such as the time required for synthesis and the resolution limitations of synthesizers, will probably yield to technological improvements. However, the inherent limitations of holograms, e.g. monochrome, static images, will continue to limit the applicability of these devices.

4.2.1.5 Composite Holograms

Composite holograms are a collection of many small subholograms, each with a different perspective view of the object. Because each eye views a different subhologram, the object is seen in depth from a particular viewpoint. With subholograms larger than about two millimeters, noticeable jumps in perspective occur during head movements. The composite hologram usually lacks vertical perspective and suffers the disadvantages of other white-light holograms.

4.2.1.6 Combination Holograms

Holograms can be made by combining the synthetic and composite types. In this technology, a computer is used to generate a series of perspective views of an object on the display. Each view is recorded on a photographic plate, just as it would be in a composite hologram. The combination hologram exhibits the same jumps of perspective seen in the composite hologram and has the reduced resolution of the synthesized hologram. One product that could be produced by this combination of technologies is the full-color hologram. Currently in the early stages of development, the full color hologram represents the nearly insurmountable problem of registering three synthetic holograms on the same holographic plate - one each for the red, green, and blue separations of a color image.

4.2.i.7 Holographic Cinema

This technology involves the generation of projection holograms on curved, reflecting surfaces. Very little is known about this technology, although there has been interest in the Soviet Union for some time. A major drawback seems to be the necessity of having the viewer centered with respect to the projection system, which means that only one person can perceive the stereo image at a time.

4.2.1.8 Pepper's Ghost

This is a commercially available embodiment of holographic technology that is used at The Haunted Mansion in Disneyland. The display consists of a volume within which three-dimensional figures are seen to revolve about their own axes and to rotate through the volume. The technology was develcped by a company called White Light Works which is involved in other holographic projects. Although the technology involved is proprietary, we can guess that each of the revolving figures may be produced by overhead or internal illumination of multiplex holograms.

4.2.2 Varifocal Mirror

The varifocal mirror concept uses the distortions produced by image reflection to synthesize a volumetric view of features displayed on a two-dimensional screen. Several different types have been developed, each of which has advantages, but only one type has been brought to the stage of commercialization. Displays based on varifocal mirrors require low ambient illumination for best performance.

4.2.2.1 Vibrating Mirror

SpaceGraph is the commercial name of a stereodisplay system based on the vibrating-mirror embodiment of the varifocal-mirror concept. It uses a silvered membrane that is oscillated sinusoidally, much like the cone of a speaker driven by a pure tone. The membrane oscillates, alternating between a concave mirror and a convex mirror thirty times per second. Concave mirrors make objects appear closer than they are and convex mirrors make them appear to be further away. Thus, a two dimensional image reflected from the surface of the oscillating silvered membrane would appear to sweep out a path in space, producing a virtual three dimensional image.

The SpaceGraph system uses this principle to generate depth. The user views the face of a CRT reflected in the oscillating mirror. Points of light are displayed on the face of the CRT synchronously with the vibrations of the mirror. Points that are displayed when the mirror is convex will appear to be further away from the viewer than points that are displayed when the mirror is concave. It is possible to construct a representation of a three-dimensional object by displaying specific pixels when the mirror is in the appropriate phase of its vibration.

This technology is ideal for presenting monochrome images of partially transparent objects, such as models of molecules or a volume of airspace, but it cannot in its current form be used to render solid surfaces. Only a limited number of pixels can be addressed when the mirror is in a particular position which limits the total number of points that can be used to represent an object. Also, the center of the mirror is constrained to move through a relatively short vibratory path because of acoustic considerations, which limits the range of depths that can be rendered. The acoustic limitations of the system also constrain the refresh rate for each pixel, resulting in noticeable flicker.

The 3D image presented by SpaceGraph is a very compelling one. No aids are required to be worn by the viewer, and the number of viewers is limited primarily by the relatively small display space. Unlike other systems in or near commercialization, SpaceGraph preserves full motion parallax by actually displaying the image in space rather than simulating spatial perception. Another consequence of the technique is robustness: differences in viewing capabilities of individuals are not aggravated by artificially imposed values such as interocular distance. Issues of resolution and real-time processing speeds can be addressed more by the computational power of the host machine than by the display technique itself. Problems relating to phospher speeds, however, need to be resolved before color can be supported.

In summary, the use of the vibrating mirror technology in C3I applications is promising. In the short term, situation assessment and data visualization tasks appear to be particularly appropriate. Eventually, its use in aspects of operational mission planning, especially for support functions to the mission planner, can be expected. However, SpaceGraph has been under development for about a decade, with limited recent progress. Until the inherent limitations of this approach are seriously addressed (acoustic limitations of the mirror, refresh rate, color, computational power needed to handle increased speeds, etc.), the application of the technology will be severely limited.

4.2.2.2 Oscillating Mirror

Displays have been developed that rely on a pair of oscillating mirrors (instead of a single mirror like SpaceGraph) to generate the third visual dimension. Each requires the user to view an image of a display screen that has been reflected from a pair of mirrors. The mirrors oscillate with respect to each other, so the optical path length from the display screen to the viewer varies. Like the SpaceGraph, this system lights pixels synchronously with the location of the oscillating mirrors to produce depth. Also like SpaceGraph, this system is capable of producing only partially transparent images, not surfaces. However, because the technique does not take advantage the way SpaceGraph does of the large change in magnification that occurs with nonplanar mirrors, the range of depths that can be produced by this system is greatly reduced. While the use of dual oscillating mirrors eliminates some of the acoustic problems of the vibrating mirror technique, implementation and synchronization of the movement of the two mirrors pose other electro-mechanical difficulties. Performance is reduced by the use of planar mirrors, and developmental work on the method has not been as consistent. As a result, the technology is not as mature as vibrating mirrors.

4.2.3 Other Volumetric Techniques

4.2.3.1 Dual Laser Beam Fluorescence

This is an interesting technology that generates volume-filling autostereoscopic images. The display medium is a transparent, gas-filled vessel within which the stereo images appear. The gas that fills the volume has the characteristic that it fluoresces when excited. Two laser beams are directed into the gas by a two-dimensional mirror system that can steer each laser beam independently. The power of each laser is too low to excite the gas to fluorescence, but the combined power of both lasers is sufficient to produce fluorescence. Thus, the gas will only fluoresce where the laser beams intersect. By steering the mirror systems and by pulsing the lasers, it is possible to energize loci within the gas that describe an object. When this is done, a three-dimensional image of that object appears. It is possible to generate dynamic as well as static 3-D objects with this technology.

Several interrelated problems hamper the continued development of this system. If the persistence time of the gas is reduced so that dynamic objects do not produce smeared images, the refresh rate becomes very high. This is limited, in part, by the laser-steering system. The excitation images produced by this system are monochromatic and they must be viewed through the gaseous atmosphere of the display volume. These problems may be alleviated by continued development, eventually providing an excellent medium for multi-viewer, full parallax viewing of dynamic 3D images, but it is unlikely that these displays will become commonplace in the near future.

4.2.3.2 Spinning Mirror

The spinning mirror system is another means of using a mirror to sweep a volume in visual space. This system, developed at MIT several years ago, uses a mirror rotating about its center on an axis that is not normal to the reflecting surface. Images reflected from the mirror describe an arc as the mirror turns, so that a two-dimensional array of pixels viewed in reflection from the mirror will describe a three-dimensional space. By addressing the pixels of a two-dimensional display screen synchronously with the angle of rotation of the mirror, it is possible to generate volumetric images of partially transparent objects. Like displays based on the varifocal mirror concept, spinning mirror displays are subject to flicker. However, because there is no oscillatory or vibrational mode to spinning mirror displays, flicker can be eliminated by raising rotational speed. The limiting factors, as described above, then become the pixel address rate and phosphor persistence. The comments regarding the applicability of vibrating mirror technology to battle management tasks (pending resolution of specific technical issues) apply here as well.

4.2.3.3 Spinning LED

The spinning LED display is similar in concept to the spinning mirror display except that in the former, the display per se, rather than an image of the display, rotates about its center. An array of LEDs positioned on a disk is rotated about an axis normal to the disk and individual LEDs are illuminated to produce outlines of objects. At any angle of view, except the axis of rotation, the viewer sees the LEDs rotating in three-space because of the different distances to the near and far edges of the disk. This display is not capable of rendering surfaces and is best viewed in darkness. Of relatively limited utility, this display type has not undergone significant recent development.

4.2.3.4 Stacked Array

Stacked array displays are composed of some number of independent display surfaces, one in front of another, containing pixels that can be switched rapidly from illuminating to invisible. Nearer pixels in an invisible state allow the illuminated pixels on successive display surfaces to be viewed. Essentially, the pixels of the stacked arrays comprise a volume of pixels that can be addressed to render an object visible in three-dimensions. This type of display suffers from poor depth resolution caused by a limited number of depth planes and from reduced image resolution caused by scatter in the intervening array planes. In its current form, it is not appropriate for battle management applications.

4.3 Continuing Developments

4.3.1 Helmet-mounted Systems

One area of increased interest and research activity is that of displays mounted in helmets for viewing by one person. An appropriate application of this technology in battle management would be the simulation of the pilot's view of a flight scenario. This technology is also being pursued for use in telerobotic situations in which the actions of the viewer are transmitted to a remote device which performs the intended action. This suggests a use in the planning and control of remotely piloted vehicles as well as manned aircraft.

4.3.1.1 Dual-Scope

The dual-scope, helmet-mounted display has been under development at NASA/Ames. This system uses binocular, backlit LCDs with 4-bit gray scales to produce the stereo images. Each LCD presents a two-dimensional view of the target environment, obtained from a particular viewpoint. When the two LCDs present corresponding images of the same environment obtained from different perspectives, the resulting image disparity is used by the visual system to synthesize the perception of stereoscopic depth. Among the capabilities of this system is the near-real-time exploration of a synthesized three-dimensional environment. This embodiment requires the addition of a six-axis head-position sensor, significantly complicating the device. At the moment the NASA/Ames systems is limited by hardware constraints to the presentation of line drawings.

Other helmet-mounted, dual-scope displays have been based on CRT rather than LCD technology. Like the NASA/Ames system, these are direct-view systems in which the display screens are positioned so that they are viewed stereoscopically by the viewer/wearer. The CRT-based display system is capable of presenting real-time, full color stereo images of the three-dimensional environment. They currently suffer, however, from the disadvantages of excessive heat, size, and mass of the required equipment.

4.3.1.2 Fiber Optic

A second type of heads-up, helmet-mounted stereoscopic display system is based on coherent fiber optic bundles that project the separate left- and right-eye images onto a partially silvered visor. Because the two images produce retinal disparity, the viewer/wearer perceives a stereoscopic image. Usually, this stereoscopic image is perceived as originating at some distance in external space, and it is seen superimposed on the external environment viewed through the partially silvered visor. The utility of this system is diminished by its reliance on the visor, which, among other things, degrades the images of other objects in the external environment. In contrast to the dual scope systems, this method allows the viewer to see both the generated and real environments. This can provide a way for a pilot, for example, to compare what he should be seeing with the actual view.

4.3.2 Collimated View Multiplexing

This display system uses a series of vertical baffles, conceptually like Venetian blinds, to separate the left- and right-eye view of a CRT. The baffles oscillate synchronously with the presentation of images on the face of the CRT to restrict the view of those images to the line-of-sight for each eye. Along each line-of-sight, the image contains perspective information consistent with that line-of-sight. Essentially, the system presents alternate left- and right-eye views, but uses the oscillating baffles to restrict each eye to seeing only its own view.

The necessary switching rate of the baffles, which must be near the refresh rate of the CRT to prevent flicker, requires the baffles to be oscillated electro-optically rather than mechanically. Current development efforts involve a three-dimensional array of pixels comprising stacked layers of two-dimensional sheets of pixels that can be changed from transparent to opaque electronically. By addressing the appropriate pixels in each layer, it is possible to generate transparent paths through the stacked layers. When vertical lines of pixels in successive layers are addressed with appropriate spatial phase shifts, transparent paths oblique to the plane of the layers can be produced. Alternate left and right oblique paths can be made transparent by changing only the spatial phase relationships.

Collimated view multiplexing is a very new technology that promises to develop into a full-color autostereoscopic display in the foreseeable future. However, at the moment, it is little more than a design concept awaiting future refinement.

5.0 SCENARIO 3D DEMONSTRATION SYSTEM

In addition to the preparation of this Final Report, this task required the development of a demonstration system that would demonstrate the use of three dimensional presentation in support of a sample Air Force C3I battle management function. This section describes the intent, implementation and results of the demonstration system, named SCENARIO.

5.1 Intent of the Demonstration

Delivery of the demonstration system was included as a task requirement for several reasons. Most importantly, it was intended to provide an opportunity for individuals to experience first-hand some of the key points presented in the study report. This is useful both in terms of supporting the report to people who have read it and in demonstrating the points of the report to people who have not. In addition, the system provides the user with a working example of 3D program code that can serve as a point of departure for gaining experience in developing software for a stereoscopic display.

5.2 Implementation of SCENARIO

The 3D Applications Study Interim Meeting, held in Rome, NY on June 8 and 9 1988, essentially marked the end of the research phase of the task and launched the demonstration development phase. Implementation issues discussed among team members and RADC personnel included the identification of 3D features to highlight, development of an outline of the demonstration application, and evaluation and selection of hardware and software to support the demonstration.

In discussing the strengths and weaknesses of 3D presentations for the demonstration, it was noted that conventional perspective graphics displayed on a 2D screen have become so sophisticated that they can address many applications without requiring 3D. Three situations were identified, however, in which it was felt that a 3D system could demonstrate superior capabilities.

The first situation was decluttering, in which elements of graphical and textual information displayed close together might be disambiguated by viewing them in their respective depth planes. An application of this feature would be air space management where both graphics and text must be viewed for a number of aircraft. On a 2D display, the positions of the aircraft can appear to overlap. The display of corresponding textual information further clutters the screen. Displaying the data at different depths was felt to provide the user with the ability to distinguish between different sets of information.

The second situation in which 3D was felt to demonstrate unique capabilities was in the display of irregularly shaped volumes and their intersections. The depiction of regular geometric volumes on a 2D display provides the viewer with enough information to imagine the shape of the part of the volume that is unseen. The shapes of irregular volumes, however, such as irregular terrain or electronic envelopes associated with electronic warfare equipment, can be very difficult to infer from a 2D representation. The difficulties are increased in applications where it is important to perceive the intersections of such volumes. The use of a display system in which the relative positions of volumes and their surfaces could be perceived in all dimensions was felt to give the viewer an important added capability.

The third situation considered particularly appropriate for a 3D display was the depiction of 3D data over time. The ability to view the movement of objects in a spatial scene was felt to provide an entirely new dimension to the user's perception of the relative locations of objects and the projected time at which objects would be at a certain point in space.

An outline was developed for the demonstration which was designed to exhibit the capabilities of a 3D display system in the context of an operational Air Force task agreed upon by RADC. In order to accentuate the user's involvement in the spatial environment, an interactive demonstration focusing on a tactical air support situation was recommended. To ensure that the attention of the viewer was focused on the airspace, it was decided that activity on the ground should be kept to a relative minimum. The ability to switch quickly between a 2D image and the same image in 3D was considered important for comparison purposes. Eventually, a rough scenario was developed in which the user's task was to select a set of waypoints from a friendly airfield to an enemy target with a minimum exposure to threats, such as enemy radars and contaminated areas.

Five hardware options for supporting the demonstration were then considered: a large screen liquid crystal display offered by Greyhawk Systems, the SpaceGraph vibrating mirror display offered by Bolt, Beranek and Newman (BBN), a Tektronix terminal or workstation equipped with their stereo shutter, a Silicon Graphics (SG) terminal or workstation equipped with a stereo shutter from StereoGraphics Corporation, and the RADC Intelligent Workstation or IWS (an Eaton 2000) equipped with the StereoGraphics shutter. The Greyhawk system was eliminated because it was only a prototype, required three minutes to refresh the screen, displayed stereo images in monochrome only, and had no interface software. Adapting the existing IWS w considered because it was the only option that did not require a change in the funding profile of the task. In spite of the availability of the equipment, it was rejected as an option due to the degraded speed and graphics performance expected, the extended learning curve for the software development team and the need to either make systems available to team members or port code developed on other systems to the IWS. The Spacegraph by BBN had the advantages of requiring no user-worn aids and running on widely available PCs. After much discussion, however, the team concluded that the limited size and capabilities of the display (monochrome wire frame), the lack of proven interface software and the fact that the system was still considered developmental by BBN outweighed the advantages for this application.

This left a choice between two stereoscopic systems by Tektronix and Silicon Graphics. The selection of Silicon Graphics was the result of considering several factors. Honeywell and Merit, who would be the primary developers of the software, both used SG equipment regularly and were very pleased with its performance. Delivery of the demo on a stereo Tektronix system would require porting software developed without stereoscopic capabilities from the team's SG systems. This placed an unnecessary additional burden on the development effort. It was also not clear that the stereo shuttering technique adopted by Tektronix performed as well as the StereoGraphics shutter. A final point in favor of choosing Silicon Graphics was the availability of systems used for demonstration at a reduced cost. In addition, the 'C' programming language which was determined to be the implementation language of choice due to its power, portability and the team's familiarity with it was included on the Silicon Graphics system at no additional charge.

Once the Silicon Graphics equipment was received, including the monitor modified by StereoGraphics, the monitor and supporting stereo gear was sent to Honeywell for development of the interface software. Honeywell then sent the system to Merit for integration with their software and review by IITRI and SRI. It was then returned to IITRI for final modifications and preliminary review by RADC. Problems with SCENARIO were cited and discussed in detail at the final technical meeting. As a result, some changes were made and additional features added to the demonstration software. An overview of the system as delivered is provided below. More detail can be obtained from the SCENARIO User's/Operator's Manual.

As implemented, SCENARIO depicts the flight of an aircraft from a friendly airfield to an enemy target. The starting and ending points of the route are pre-defined, and the resulting default flight path is a straight line from airbase to target. Also defined in advance are friendly and enemy sensor sites, often associated with weaponry positions, and clouds of radioactive contamination that move across the scene as they disperse. The task of the user is to modify the flight path of the aircraft so as to minimize exposure to both contamination and the threat domes which indicate the electronic coverage of enemy sensors. To support this task, the user is able to interactively define the route and preview the aircraft flying this route in near real-time. At any time, the user can replan the mission from any waypoint.

The demonstration can be run using either of two terrain databases. Original plans called for the use of terrain data of a 50 km by 70 km region centered on the East/West German border, the Fulda Gap. During development, it was determined that an available terrain database of the San Luis Obispo region of southern California provided more detail of a larger area (77 km by 110 km) as well as a more diverse range of altitudes. Both terrain databases were delivered with the demonstration. In both cases, the terrain is displayed as an elevation shaded map in three dimensions.

In running the demonstration, the user has the ability to select between a 2D plan view of the scene, a 2-1/2 D perspective view, and a 3D stereoscopic view. Since the demonstration is viewed through an active stereo filter, 2-1/2 D is achieved by setting the stereo disparity to 0. The 2D plan view (or god's eye view) is a special case in which the viewpoint is directly overhead. The user also has the ability to move the viewpoint of the observer to any location relative to the terrain, including the ability to zoom in and out of any scene.

Because corresponding databases of actual cultural features were not available to the demonstration implementation team, it was necessary to create entities that appear on the landscape. As originally implemented, the only items created were flat icons of tanks, cities and waypoints, all of which floated above the surface of the terrain and were identifiable only from above. Upon review by the team and RADC, it was decided that 3D icons were necessary which could be scaled according to distance from the viewer, identified from any angle and that could not be mistaken for actual scale renditions of the items they represented. 3D icons were subsequently developed for missile launchers, cities, waypoints, airfields and the aircraft. It also became apparent that the lack of surface features, coupled with smooth shading of the terrain, made it very difficult to discern the actual surface of the landscape and to judge the relative positions of landscape features. Two efforts resulted which attempted to provide additional monocular depth cues. First, the algorithm for generating terrain color was modified to allow for some variability of color at a given altitude. This resulted in providing a sense of texture to the terrain which added some perspective cues. Second, the number of city icons was increased to provide additional cues for perceiving distance.

In its final form, SCENARIO allows the user to interactively enable/disable the following classes of overlays at any time during the operation of the demonstration: cities, airbases, command centers, targets, friendly forces, enemy forces, contamination particle clouds, threat domes, text, the flight path of the aircraft, and a superimposed grid that indicates surface distance.

An additional feature, called 'dynamic slides' was developed to allow the user to store multiple versions of display settings (such as overlay selections, viewer location, the position of the aircraft, etc.) to which the viewer can return with a single keystroke. These captured images, from which the user can then resume execution of the particular scenario, were originally intended for use in demonstrating the SCENARIO system by creating and saving particularly compelling views in advance. In routine use, however, the image-saving capability has proven to be an excellent tool for storing points in the scenario to which the user may want to return for purposes of further development or comparison.

5.3 Review of the Demonstration

The process of developing and reviewing the SCENARIO demonstration system provided insights into the use of 3D stereoscopic displays for operational tasks that had not been considered. Much of this experience was directly related to the stereoscopic technology with which the team was working. In particular, issues raised in reviewing the initial demonstration related to the need of the developer to understand the many aspects of human viewing that contribute to (or detract from) the perception of depth.

One example of this was the original decision to minimize the presence and activity of entities on the ground in order to focus the viewer's attention on the three dimensional airspace. Upon reviewing the demonstration, it became apparent that the lack of surface features resulted in a poorly defined terrain surface. This distracted the viewer and detracted from the sense of relative depth by eliminating important monocular depth cues. An effort was made to reduce the effects of this problem by further populating the surface terrain with scalable (i.e., size automatically adjusted by the system depending on distance from viewer) 3D icons of cities and targets.

Additionally, the lack of surface features was attributed to the use of a terrain shading algorithm based on altitude rather than on lighting models. The shading of the terrain for SCENARIO is accomplished by assigning a user-specified range of 240 shades of color to 240 altitude segments comprising the range of terrain altitudes from the lowest point to the highest. The coloring scheme applied to the SCENARIO terrain was a standard for physical geography, ranging from deep greens to light browns as altitude increases. This scheme was used because it was easily understood and implemented by the development team. Another alternative would have been to use the internal lighting models provided with the Silicon Graphics computer. This, however, would have placed additional burdens on the development of the system and on its operation, since the terrain coloring would need to be recalculated for each display. Because the team felt that the altitude shading was sufficient, it decided not to pursue the use of lighting models at the expense of remaining time required to implement the rest of the demonstration.

Two problems eventually surfaced regarding the use of the technique for the demonstration. Upon review of the demonstration it became apparent that the use of altitude-based shading presented a blurring of surface features. The purpose of the technique is to present a smooth transition of shading as altitude changes. Viewed from above in high resolution, the viewer is able to determine relative terrain features without the use of 3D. Viewed from a low angle and up close, however, mountain ridges of approximately the same height were the same color and blended together.

The second problem was a consequence of the terrain data itself. The region included in the San Luis Obispo sample was chosen because it contained a greater range of altitudes. Unfortunately, one corner of the sample included a particularly high peak. When the range of altitudes was computed and the spectrum of colors assigned to specific altitude sub-bands, the result was that a large portion of the high altitude colors were used only for the high peak, leaving the vast majority of the terrain in similar shades of green. Several possible improvements were discussed, such as changing shading of the terrain as it receded from the viewer or modifying the terrain data to reduce the altitude of the peak. The lack of time and labor hours, however, permitted only limited modifications to the existing system. The algorithm for determining the color of a particular pixel was modified to allow for some variability in the shade of color assigned, with the intent of providing a sense of texture to the terrain.

In addition to posing unique design issues relating to the effective use of 3D, the development of SCENARIO provided a first-hand opportunity to explore the capabilities and constraints of stereoscopic image presentation. It became quickly apparent that the implementation of stereo graphics was not simply a matter of generating dual images. The ease with which stereoscopic depth was perceived varied markedly for different people as well as for a single viewer during different sessions. In general, however, it was noted that the ease and comfort of perception of the stereo environment improved as the user worked on the system. In fact, the degree to which depth was perceived increased with continuous exposure. The problems encountered in the use of the stereo display were essentially the inconsistency and unpredictability of the viewer to perceive stereoscopic depth by successfully fusing the stereo images. The greater the intended stereoscopic effect (as determined by the adjustable viewing parameters), the more pronounced the problem of immediate and consistent perception. By providing user control over the setting of the viewing parameters, the development team felt that the viewer could adjust them to maximum effect during the session and the software developer could experiment with the capabilities of the stereoscopic technology.

The SCENARIO demonstration software provides the user with an example of 3D display technology applied to a battle management application. Project constraints in terms of team experience with 3D development, budget and time restrictions, and equipment performance capabilities necessarily limited aspects of the implementation. In most cases, these limitations can be overcome by further development of the system. In addition, the combined hardware and software provide a powerful and expandable stereo-equipped 3D graphics workstation for continued exploration and development. The SCENARIO source code contains examples of many aspects of stereo programming on the system, and its modular structure facilitates both enhancement of SCENARIO as well as the use of its module in other programs.

6.0 CONCLUSIONS

A potential exists for achieving real and significant improvements in the performance of certain battle management activities as a direct result of the use of three dimensional displays. Primary anticipated benefits are a decluttered screen image providing greater accuracy and ease of use by the viewer; an improved accuracy in perceiving the mass, surface areas and intersections of volumetric forms; and an increased insight into the relationships of objects as they interact over time. C3I battle management functions that can put these enhanced capabilities to the best use are in the areas of situation assessment and operational mission planning, particularly applications which involve the presentation of battlefield dynamics for purposes of evaluation. These situations make optimal use of the unique advantages of spatial and temporal modeling afforded by 3D displays.

The ability to realize the potential benefits of 3D displays is constrained by the state of available technology. Factors important to the successful application of 3D technology to C3I battle management tasks include image resolution, full color capabilities, real-time processing and display speeds, full motion parallax, robust multiviewer support, and minimum requirements for user-worn aids. Techniques that rely on photographic or computer-generated imagery typically provide the resolution required, though photographic systems require image collection instead of dynamic generation and typically involve processing times inappropriate for real-time efforts. A related issue, however, is the display volume or space. The SpaceGraph, for example, provides a very compelling image partially because of the resolution achieved in a relatively small display volume. Full color is currently achievable with some computer graphics systems. The demand for real-time display capability limits the effectiveness of several techniques, although in many cases real-time processing is a function of the underlying computer power. Preservation of full motion parallax in a display system has been achieved in only one commercially available system, the SpaceGraph vibrating mirror system.

Several techniques allow the image to be viewed by more than one observer, but the problem of human vision variability and visual fatigue affects all 3D methods to some degree. Studies indicate that a significant percentage of the general population (between 15% and 30%) are in some way stereoscopically impaired. Because of the potentially harsh, often uncontrollable conditions under which the targeted user must be able to operate, it is critically important to minimize the negative effects of the technology on the user. A fieldable system should be equally usable by anyone and require no special training or capabilities. Ideally, this would include the requirement for user-worn viewing aids. In addition, the viewer must be able to tolerate prolonged use of the system with a minimum amount of effort or risk of visual fatigue. While technological research continues to spur new developments in 3D display techniques, very little directed research into the human factors issues associated with the technology has been performed. Those marketing the new technology will continue to determine the direction of its development until studies are performed that clearly relate these new and different techniques to human perceptive abilities and identify their effects, both positive and negative.

A final issue in the commercial development and eventual deployment of 3D systems is the lack of suitable input devices. While the viewer is receiving three dimensional output from the system, he has no easy way to move a cursor or otherwise select points within that space. Some attempts are being made to fill this gap. In an evaluation of 3D cursors (3D trackball; conventional X, Y, yaw; 3D mouse with selectable XY, XZ, YZ planes; solid 3D thumbwheels; planar thumbwheels; Z-axis slider with X- and Y-axis thumbwheels), the fewest positioning errors were made by subjects using the planar thumbwheels, followed by the Z-axis slider type cursor. The 3D trackball and mouse performed the worst. The evaluation concluded that vector-oriented cursors were better than planar (XY, XZ, YZ) or free-space (trackball) cursors, though none of the devices were considered to be very good.

The SCENARIO demonstration system was developed to demonstrate the benefits of 3D to a specific battle management task area. In deciding which display technology to use, commercial availability limited the choice to the SpaceGraph vibrating mirror and a stereoscopic shuttering system. The selection of the stereoscopic technique was based in large part on the relative commercial maturity of the product and of the supporting hardware and software interfaces. The decision to purchase an implementation based on Silicon Graphics and StereoGraphics equipment was the result of team familiarity with and access to equivalent equipment as well as cost restrictions. The alternative was to purchase the SpaceGraph and attempt to develop the necessary support software while learning how to program the device and develop an acceptable demonstration with the technological constraints of the display device. All of these decisions were affected by the limited effort funds and relatively short amount of time in which to acquire, install and develop a 3D demonstration system. As a result, the team favored the most conservative option, which resulted in providing the client with a powerful and expandable graphics workstation with a stereoscopic display capability.

The demonstration software was developed around a mission planning scenario mutually agreed upon by the study team and the government. While the actual development of software which supported the stereo system was not much more complex than software for conventional displays, it did require an added effort. As the system was being developed, many lessons were learned by observing the stereo image and evaluating its effect. Some decisions, such as originally deciding to project all images behind the plane of the screen (positive parallax), seemed obvious until the effects of viewing objects in front of the screen (negative parallax) were experienced. In an effort to accentuate the 3D features of the display, decisions were made which were later recognized as having reduced the effectiveness of the display by removing valuable monocular cues. Most design decisions, such as committing to a terrain coloring scheme based on altitude rather than using available system lighting models, were based on an estimate of the available labor hours. Others, like the default terrain resolution settings, reflect computational restrictions of the system speed.

Building SCENARIO was a 3D learning process as well as a software development one. The resulting program suffers from some deficiencies that can be corrected as experience with the system is gained. As delivered, however, the SCENARIO code provides the user with the capability to explore the use of a stereoscopic display in support of a particular C3I function. As images and scenes are discovered or generated that demonstrate certain characteristics of the technology, they can be saved for later display and examination. Access to the source code allows the system to be enhanced as desired, using either existing routines that support the stereo display equipment as working examples or incorporating newer and more powerful algorithms.

In summary, given the current state of the technology, three dimensional displays can provide the viewer with a perceptual reconstruction of three-space that is not achievable otherwise. The use of 3D may be important when monocular cues alone provide ambiguous depth information. Stereoscopic 3D can resolve those ambiguities, though depending on the technology, it may be at the potential risk of some viewer discomfort.

7.0 REFERENCES

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